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Effect of Boundary Conditions on the Back Face Deformations of Flat UHMWPE Panels

by Timothy G Zhang, Sikhanda S Satapathy, Lionel R Vargas-Gonzalez, and Shawn M Walsh

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EFFECT OF BOUNDARY CONDITIONS ON THE BACK FACE DEFORMATIONS OF FLAT UHMWPE PANELS

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ABSTRACT

The back face deformation (BFD) characteristics are important in assessing the load transfer from the helmet to the head due to blunt impact. We carried out a series of ballistic experiments to investigate the BFD in flat panels made of Ultra-High-Molecular-Weight-Polyethylene (UHMWPE). Spherical projectiles were used at velocities in which the panels were not perforated. In our study, we used three different boundary conditions, namely, clamped-corners, clamped-edges and free boundary condition (the panels are suspended by two strings). The experiments were modeled in LS-DYNA. Existing composite material models were found not to be adequate in capturing the observations. Therefore, we calibrated the constitutive parameters of a composite material model to the experimental conditions. Tiebreak contacts were used to model the delaminations in the composites. The calculation showed reasonable agreement with the experimental data for the clamped-corners and free boundary condition cases for the peak BFD, remaining thickness of the composite and the delamination behavior. The model is useful to assess the size-effects and boundary proximity effects under blunt impact scenarios.

1. INTRODUCTION

The two parameters that determine the protection capability of a helmet are the ballistic performance, indicated by V_{50}, and back face deformation (BFD). The former value is the velocity at which the bullet has 50% probability of being stopped by the helmet. When the bullet is stopped by the helmet, large back face deformation can cause blunt trauma behind helmet if the helmet strikes the head. The helmet response is governed by the helmet material properties, helmet curvature, shape and size, bullets type, etc. Therefore, in establishing the model parameters from simplified geometries, the role of the geometric parameters, such as proximity to boundary, shape, etc. must be taken into account.

In the literature, research has been carried out on the effects of boundary conditions on the ballistic performance (energy absorption) for fabric composites. Shockey [1] investigated the boundary condition effects in fabric targets. Test results showed that a fabric gripped at two edges can absorb significantly more energy than the same fabric gripped on four edges. When the material is clamped at four edges, the primary yarns deform and fail quickly. Zhang [2] carried out a numerical study of the effects of clamping type and clamping pressure on the ballistic performance of woven Kevlar, and found that the composite can absorb more energy when it is clamped at two opposite edges compared to being clamped at four edges. In that work, the effects of composite size were also studied. Singletary [5] studied the effects of boundary conditions and panel sizes on V_{50} for Kevlar KM2 fabric. The effect of clamp designs, such as four sides clamped, two sides clamped, circular clamp, diamond clamp, corner plate clamp, and corner point clamp, on the ballistic performance was studied in Nilakantan [7].

In this study, experiments were conducted to understand the effects of boundary conditions on the BFD in flat UHMWPE panels. UHMWPE possesses high tenacity and high strength compared to Kevlar, as a result of which it is the material of choice for Enhanced Combat Helmet (ECH) design. Examples of this material are DSM's Dyneema® HB80 and Honeywell®'s Spectra Shield II® SR-3136. The combination of novel manufacturing and new material development led to the development of the ECH, which exhibited a historically high >37% improvement in fragment resistance on average over the Army Combat Helmet (ACH), the incumbent Army helmet.

Three boundary conditions were used, including four corners clamped, four edges clamped and panel suspended by two strings. A numerical model developed in our previous work [3] is used to model these experiments. Two additional panel sizes were also used in the numerical simulations to explore the size effect. To our best knowledge the effect of boundary conditions on the BFD for UHMWPE material has not been reported in the literature.

2. BACK FACE DEFORMATION EXPERIMENTS

The BFD experiments were performed at ARL's (Army Research Laboratory) experimental facility. Digital image correlation (DIC) was used to record the deformation in the back face of the panels during the experiment. DIC can capture the full field displacement and strain of a panel through optical means. Two Photron SA5 cameras were arranged 15° off axis behind the panel to collect high-speed stereoscopic imagery of the panels, as shown in Figure 1. The deformation of a high-contrast dot pattern, applied using preprinted temporary tattoos, was captured at ~50,000 fps during the ballistic event and analyzed to obtain the displacement and velocity data.

Figure 1. Test setup for BFD tests (panels are suspended by two strings).

For the BFD experiments, three different boundary conditions: four corners clamped, four edges clamped and free edges were used to investigate the boundary condition effects, as shown in Figure 2. Figure 2(a) shows the UHMWPE panels clamped to a steel frame at four corners. This is not a well defined boundary condition for numerical simulation. The corners can slide along the frame or rotate during the experiments, and the out-of-plane deflection in the top and bottom edges are constrained by the steel frame. For the second boundary condition experiment, the panels were clamped by two steel frames, which were fastened by bolts. There were no holes in the composite in order not to weaken the panels by generating initial damage/delaminations. Similarly, the panels can slide between the two frames and the amount of sliding depends on the fastening torque in the bolts. In the tests, the torque was fixed at 30 ft-lb. Nilakantan [6] used similar boundary conditions in the tests and observed fiber slippage between two steel frames. As the bolt torque increases, the slip decreases. For the free boundary condition experiment, the panels were suspended by two strings through two holes near the top edge.

(a) (b) (c)

Figure 2. Boundary conditions in the BFD tests, (a) four corners clamped, (b) four edges clamped, and (c) suspended by two strings.

All of the panels used in the experiments reported in this paper were 0.30 × 0.30m (12in) × 7.8 mm (0.3 in) thick and composed of 55 layers of cross-ply UHMWPE sheets. The flat panels are prepared from unidirectional layers of UHMWPE stacked at alternating 0 and 90 deg orientations. Table 1 shows the test number, boundary conditions and impacting velocity V_0. The bullet used in the tests was 0.5in steel sphere. The impact velocity was selected so that the bullet would not perforate the panel. The impact velocities were around 300 m/s when the panels were clamped at four edges or suspended by strings. However, only higher velocity data is available for the case where all four corners were clamped. Strictly speaking, only the clamped and free boundary condition experiments are comparable since the impact velocities for these cases were similar. We include the higher velocity data for clamped-corners case for two reasons: to compare with numerical model, and to derive insight into the boundary condition effects on wave dynamics and BFD for this case. In future, clamped-corner panels will be tested at ~300 m/s for direct comparison with other two boundary condition cases.

Table 1. The test conditions for BFD tests.

Test	Boundary Conditions	Impacting Velocity V_0 (m/s)
223	four corners clamped	440.6
262	four edges clamped	297.0
267	free	292.6

The time histories of the back face center deformation for the three different boundary conditions are given in Figure 3. The BFD data were recorded every 25 μs using DIC. The time-zero did not correspond to the impact time. The time-zero corresponds to the time of the frame (-25μs) before the frame which had a nonzero BFD. For free boundary conditions, the plate could rotate after impact. The BFD was corrected by subtracting the displacement at four corners so that it could be compared with other boundary condition experiments in which the corners were clamped. The uncorrected curve is also shown in the plot. After impact, the back face starts to deform and rebound after the peak. The peak BFDs are 28.7, 16.1 and 16.3 mm for clamped-corners, clamped-edges and free boundary conditions, respectively. Thereafter the BFD oscillates with a period of about 3ms as seen in Figure 3. The impacting velocities were close for tests 262 and 267; consequently the BFD time histories are almost the same until peak BFD for the two tests. The boundary conditions appear to have effects after peak BFD is reached. When the panels were suspended by two strings, the corners did not move (corrected and uncorrected curves were nearly identical) before the peak BFD was reached.

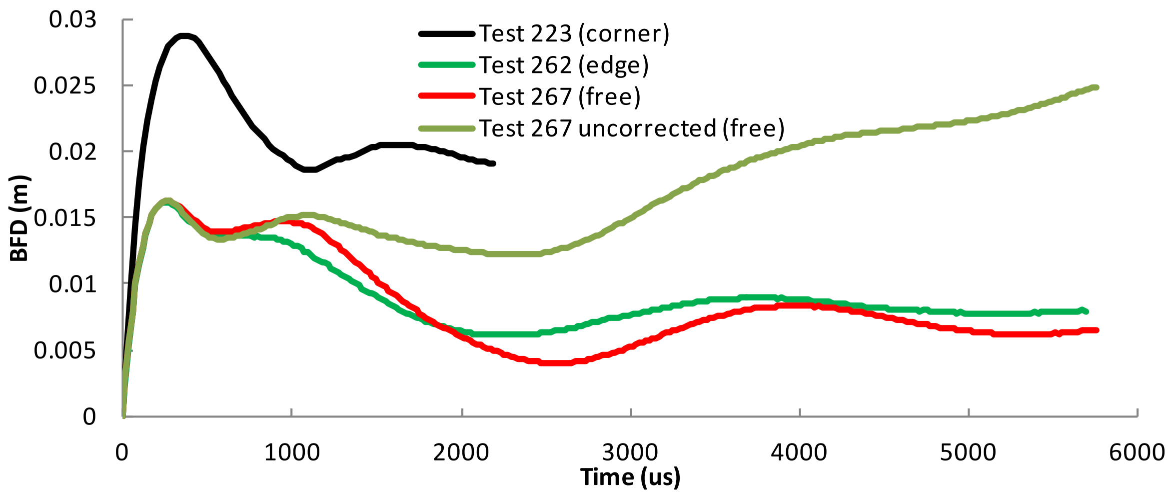


Figure 3. The time histories of BFD.

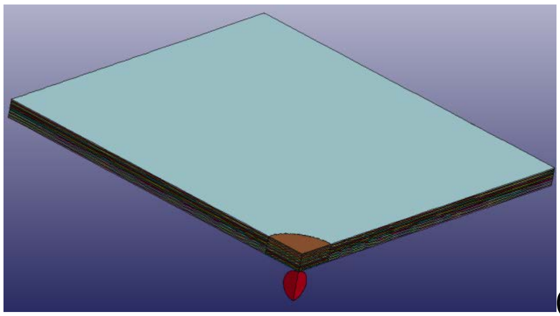
The experimental data for the clamped-edge experiment and the free edge experiment indicate nearly identical peak BFD. The lack of the influence of boundary conditions on the peak BFD is due to the time taken for the reflected waves from the edges to arrive at the panel center depends on the panel size. For the panel size chosen, the peak BFD occurs before the boundary condition effects are felt through the reflected waves as was confirmed through simulations reported in the following section. In the following section, we describe a numerical model in LS-DYNA to simulate the experiments to understand the effects of the boundary conditions.

3. NUMERICAL MODEL

The spherical bullet and panels are symmetric along two principal directions that are oriented along the directions of the 0 and 90 fibers. Therefore, only one-quarter of the geometry needs to be modeled with symmetry boundary conditions applied. Friction was not considered in this study.

Existing composite material models were found not to be adequate in capturing the experimental observations in our earlier study on flat panels [3]. In that study, we calibrated the constitutive parameters of a composite material model available in LS-DYNA to match the experimental results. In this paper we have adopted the same material model, details of which are described in [3].

Three-dimensional hexahedral elements were used in our model. Large deformation was observed to occur only near the impact zone in the DIC data, and the deformation amplitude was observed to reduce farther away from the impact region, at least until the bullet perforates or stops in the panel. Therefore, we used non-uniform meshes—very fine meshes (~0.3 mm in size) near the impact region and coarse meshes (up to 15 mm in size) elsewhere, as shown in Figure 4. The total number of nodes and elements are 5773 and 5636 for one layer. Fiber breakages were expected to occur only in the impact zone. Therefore, contact erosion was used only for the impact zone for improved efficiency.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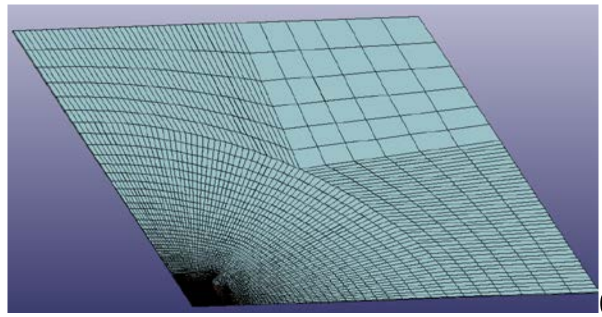
(b)

Figure 4. FE model for (a) bullet and panel, and (b) one layer.

The boundary conditions were simplified in the numerical model. When the panels were clamped to the frame at four corners, no noticeable motion of the composite panel was observed at the corners in the experiment. Therefore, the frame was not modeled, and panel corners were clamped in the computation. To validate this approximation, we carried out one simulation where the frame was included in the model; however, only a minor difference was observed in the deformed shapes. The details can be found in [3]. All of the displacements and rotations were constrained at the edges for the panels clamped at four edges, while there were no constraints applied to the panel edges/corners when it was suspended by two strings. Of course, this is not valid after peak stress waves reach the boundary, after which the plate starts to rotate. Since the peak BFD occurs prior to arrival of the reflected waves from the boundary, this approximation is valid for peak BFD.

There are 55 layers of cross-ply UHMWPE sheets in the panels. If the panel is modeled into 55 layers, large computational resources would be necessary primarily to model contact between the layers. Therefore, we used a reduced number of “fused” layers (in this case, 20), keeping the panel thickness the same, i.e., the layer thickness in the model is about 55/20 = 2.75 times the layer thickness in the experiments. We recognize that modeling all 55 layers would be more accurate and capture delamination behavior better. However, we found that the use of 20 fused layers produced satisfactory agreement with the experimental results in general, and was computationally more expedient.

Delamination is a very common failure mode in composite laminates, and was observed in our experiments as discussed in the following section. Modeling delamination in UHMWPE panels has been attempted earlier [4], and is still a challenging task. In Reference [4], a progressive damage model was developed in ALE3D to simulate the high-speed penetration of UHMWPE panels. ALE3D uses an arbitrary Lagrangian-Eulerian framework. The delamination could be captured with an internally stored crack strain. ParaDyn, a Lagrangian code, was also used in the simulation, in which the composite was modeled with orthotropic ([0°/90°]) sliding layers with automatic contact (SAND) defined.

In this work, we used tiebreak contacts to model the delaminations. Tied contacts *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK between adjacent layers are defined. Initially the layers are tied together. The tied contact fails when the following failure criterion is satisfied:

$$\left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 \geq 1$$

where NFLS is normal failure stress, SFLS is shear failure stress, which are calibrated to match the experimental data, and σ_n and σ_s are tensile stress and shear stress, respectively, which are computed in the simulation.

4. NUMERICAL RESULTS

The model described above was implemented in LS-DYNA to simulate the BFD experiments. LS-DYNA was chosen as it contains the composite material model necessary for modeling large deformation and various failure modes observed in UHMWPE panels, which are not readily available in other hydrocodes.

4.1 Numerical Model Results

Table 2 lists the comparisons of the peak BFD and number of intact composite layers between LS-DYNA simulation and experimental data. It can be seen that the agreement is good (BFD predictions and test data are within 5% difference, number of intact layers do not differ by more than one) between simulation and experimental data for the cases of corner-clamped and free boundary condition. However, the agreement is poor when the panel edges were clamped, which is likely due to the incorrect representation of the boundary condition in the numerical model. In the model, the four edges were constrained against displacement and rotation. However, the panels were held between two steel frames in the experiments and the panel edges could still slide with friction (friction depends on the fastening torques) between the two frames. Including the clamps and their friction behavior would perhaps improve the simulation results.

Table 2. Comparisons between model predictions and test data.

Test	Boundary Conditions	Peak BFD (mm)			Number of estimated intact “fused” layers (out of total 20 fused layers)	
		Test	LS-DYNA	Difference (%)	Test	LS-DYNA
223	four corners clamped	28.7	27.3	5.0	8	9
262	four edges clamped	16.1	9.5	40.9	15	12
267	free	16.3	16.7	2.5	15	15

The time histories of BFD are given in Figure 5. The experimental data have negligible difference up to 500μs for edge clamped and free boundary conditions. The computational simulation indicates that for these cases, the panels were large enough that the peak BFD was reached before the reflected waves from the boundary arrive at the panel center.

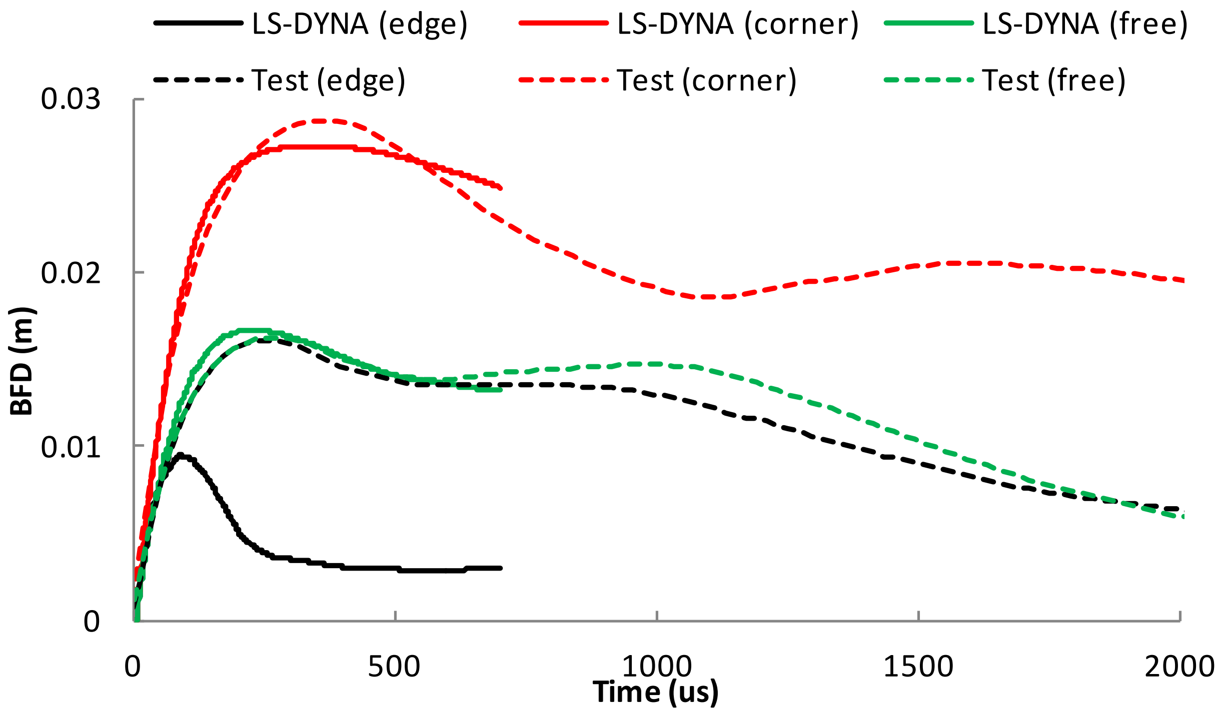

Figure 5. Time histories of BFD.

Figure 6 shows the damage in the panels from post-test CT scan of the UHMWPE panels and the simulation results. Only a part of the panel containing the center hit-location was scanned for four corners clamped test to obtain higher scan-resolution. For the other two cases, full panel scans were obtained as the resolution was found to be sufficient for full-panel scan. In both experimental and simulation results, it can be seen that a hole, similar in size to the bullet, forms around the bullet by breaking the fibers. Many layers delaminated in the panel, especially a major delamination occurs at the location where the bullet stops. For the two lower velocity experiments, the sphere rebounded. When the four edges were clamped, the hole was a little deeper, but the remaining thicknesses in the composites were similar. The simulation results are for the shapes corresponding to peak BFD, but the CT scan shows the final deformation. After peak BFD, the panels rebound and oscillate before equilibrium. In the model, no damp was added, as a result, the panels would not stop oscillating to attain the final shape. Therefore it is not surprising that the peak BFD in the simulation results is larger than the final BFD in the experiments. However, the remaining thickness, extent and nature of delamination from the simulation were close to the experimental results.

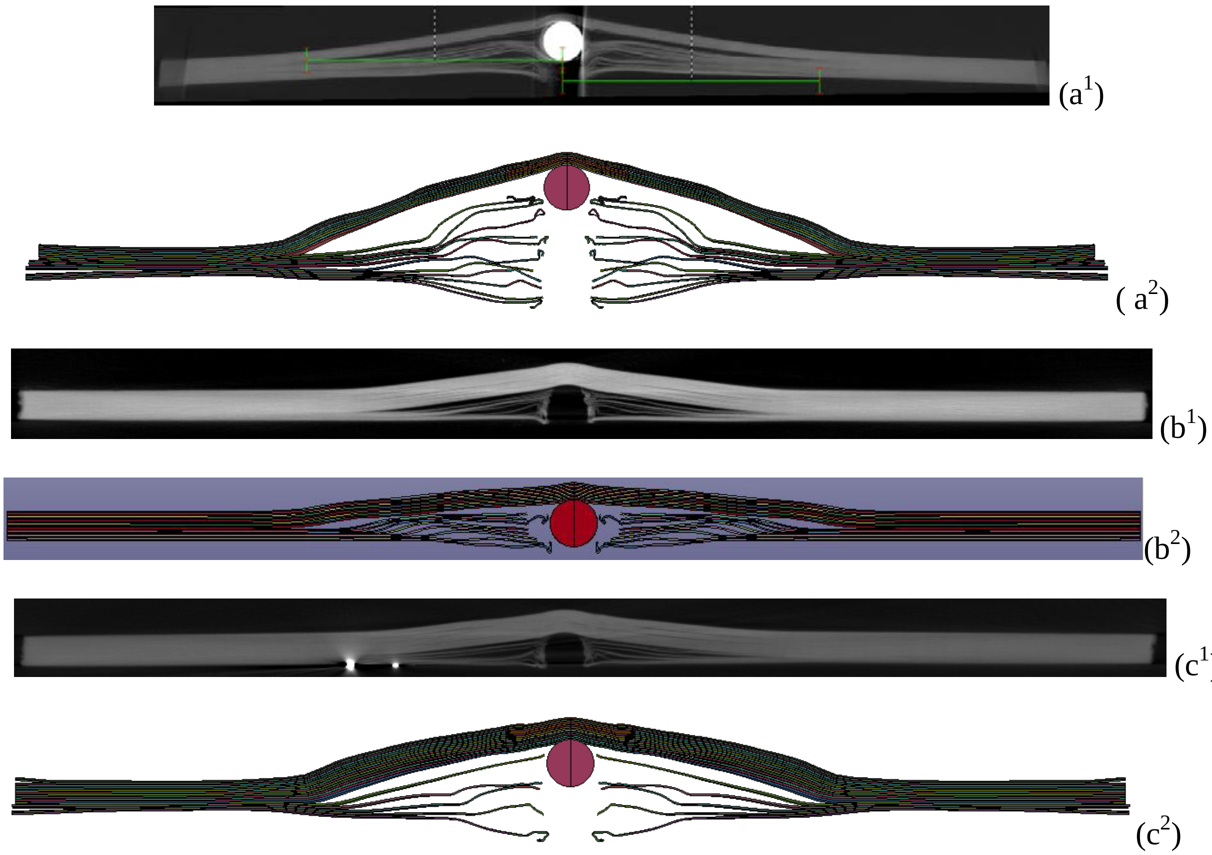

Figure 6. Delaminations in the panels for (a) four corners clamped, V_0=441 m/s, (b) four edges clamped, V_0=297 m/s, and (c) free, V_0=301m/s. (superscript 1 for CT scan from post-ballistic panels, superscript 2 for LS-DYNA prediction).

4.2 Effect of Boundary Conditions and Panel Sizes

As described earlier, one set of experimental results (corner-clamped case) was obtained at a higher impact velocity than the other two. Therefore, no direct comparison could be made on the boundary condition effect strictly from the experimental data. However, since the computational model was calibrated to match these experiments individually, the boundary condition effects could be studied using the computational model. Therefore, the numerical models were exercised at the same impact velocity of 292.6 m/s (which is the impact velocity for free boundary condition case) for all three boundary conditions. In addition to 12in panel size, two additional sizes, 6in and 10in were also used to investigate the size effects.

Figure 7 shows the effect of boundary conditions on the time history of BFD for three panel sizes. The BFD is always smallest when the panel edges are clamped. The time histories of BFD are the same when the panels are suspended by strings or clamped at corners until the corner constraint takes effect. After impact, the waves propagate mainly along primary fiber-directions to the panel edges and the edges start to move toward the panel center, as illustrated in Figure 8. This movement is restrained by the corners if the corners are clamped.

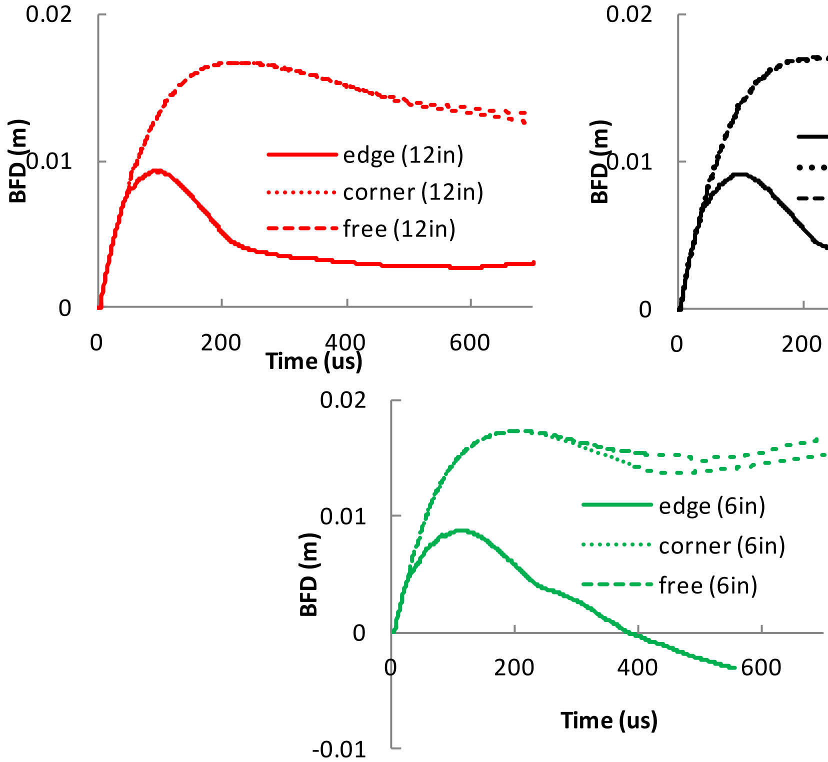

Figure 7. Effect of boundary conditions on BFD.

Figure 9 shows the time histories of edge center (the location is indicated by the arrow in Figure 8) displacement toward the panel center for 6in panel for both free and corners-clamped boundary conditions. The displacement can be up to 3mm. When the corners are clamped, the displacement drops faster after the corner effects show up. The time before the corners affect the BFD increases with the panel size. Therefore the discrepancy occurs later for larger panels. For panels 6in and larger, the boundary condition effect show up after the peak BFD is reached. If the panel sizes further drop, the peak BFD would be affected by the boundary conditions. We did not conduct additional numerical simulations for panels smaller than 6in.

Figure 8. Sample deformation result from simulation in the panel showing the edge center movement toward the center (free boundary condition).

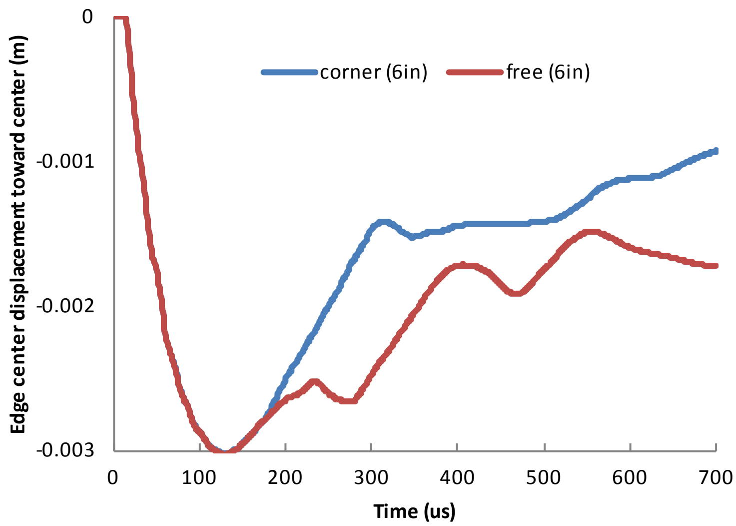

Figure 9. The time histories of edge center displacement toward the panel center (6in panel).

The effects of panel size are shown in Figure 10. As the panel size increases, the peak BFD increases when the panel edges are clamped. However, the peak BFD decreases as the panel size increases for both free and corners clamped boundary conditions.

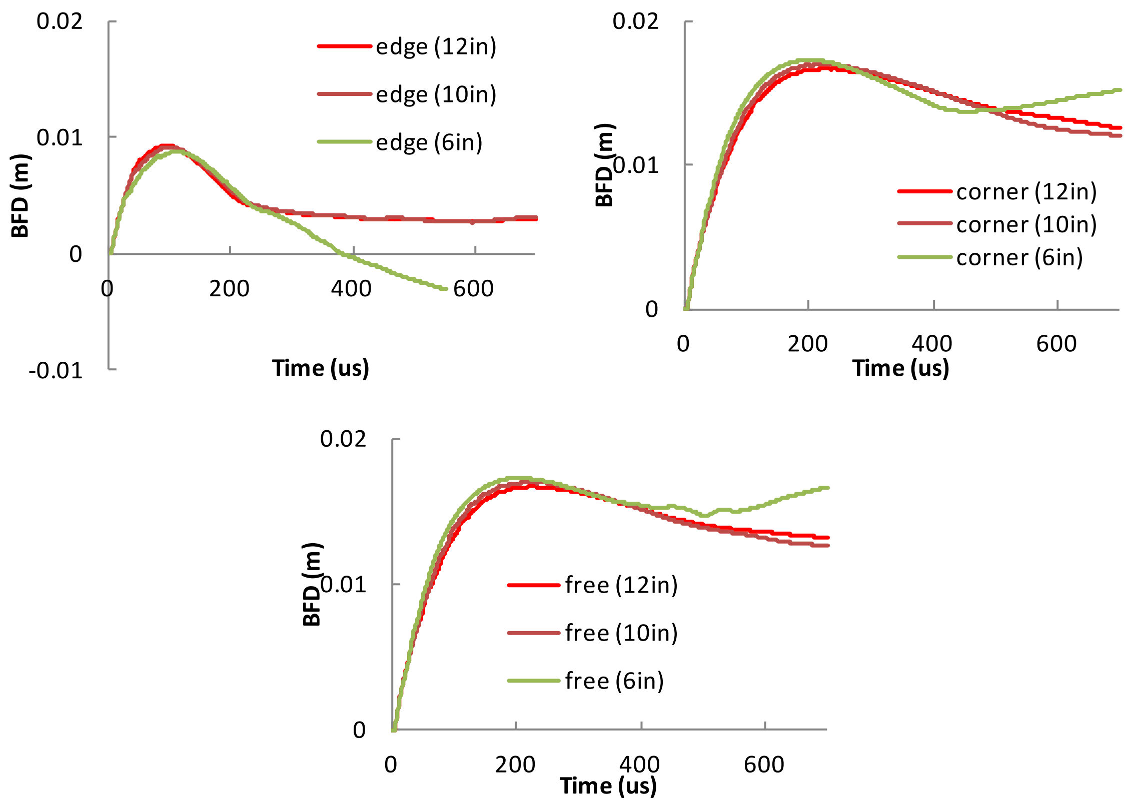

Figure 10. Effect of panel sizes on BFD.

The peak BFD and number of intact layers are compared in Table 3 for different panel sizes. The peak BFD and layer number of intact material are the same for clamped-corners and free boundary conditions. As the panel size decreases, the fiber is stretched more leading to earlier failure, and hence the number of intact layers drops when the edges are clamped. However, less material is failed when the panel size decreases for both clamped-corners and free boundary conditions.

Table 3. Effect of boundary conditions and panel sizes on peak BFD and number of intact layers.

Boundary Conditions	Peak BFD (mm)			Number of intact layers		
	6in	10in	12in	6in	10in	12in
four corners clamped	17.3	17.0	16.7	16	15	15
four edges clamped	8.8	9.2	9.3	8	11	12
free	17.3	17.0	16.7	16	15	15

5. CONCLUSIONS

Ballistic experiments were carried out to investigate the effects of boundary condition on the peak BFD in flat UHMWPE panels. The boundary conditions include four corners clamped, four edges clamped and free edges. The experimental results showed that the boundary conditions did not have a large effect on the peak BFD for 12in size panels for edge-clamped and free boundary conditions.

A numerical model developed in our previous work was used to simulate the BFD experiments. Tiebreak contact was employed between adjacent layers to model delaminations. Boundary conditions were simplified in the model. The simulation results show good agreement with the experimental data when the panels were clamped at four corners or suspended by strings. However, the agreement was poor when the panel edges were clamped by two frames, which turned out to be a consequence of incorrect representation of the boundary conditions in the model.

The effect of panel sizes was also explored with the numerical models. As the panel size decreases, it takes less time for the boundary conditions to take effects and influence the BFD.

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RDRL WMS
M VANLANDINGHAM

INTENTIONALLY LEFT BLANK.